Numerical Simulation of Pump Oil for Rotary Compressor under Different Crankshaft Structures

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ABSTRACT

The crankshaft oil pump system is an essential part in the rotary compressor. There are two kinds of crankshaft inner-hole structures for the oil pump system, such as the straight-hole and the horizontal-hole. Differences between the straight-hole and the transverse-hole are not only in the processing mode and cost, but also on the oil mass flow of the pump. In this paper, based on the CFD software, the fluid field of whole compressor exhaust chamber under different speeds is simulated, and the pressure pulsation curves of crankshaft straight-hole end and transverse-hole end are obtained, which are used as the boundary conditions of oil pump system simulation. Finally the impact of two structures with the straight-hole or the transverse-hole on the oil pump under different speeds is got. The pumping oil quantity with the transverse-hole structure is relatively low at low speed and is less than the straight-hole structure at high speed. That means the crankshaft transverse-hole structure is more suitable for the frequency conversion compressor. The results of CFD simulation are indirectly verified by the long-term and reliable test.

1. INTRODUCTION

There is a crankshaft oil pump system inside the rotary compressor. When the compressor starts, the crankshaft rotates with high speed. During this process the lubricating oil in compressor bottom overcomes the gravity and surface tension and rises along the inner wall of the crankshaft, finally reaches the height of each bearing and goes through the radial spraying hole into the bearing to lubricate the parts with high-speed movement, such as cylinder, piston and crankshaft etc. Lubricating oil not only can reduce the friction and abrasion of wear, but also can play the role of sealing, cooling and reducing operation noise. Good lubrication condition is an important guarantee for the long-term and reliable work of the compressor. In the rotary compressor oil pump system, considering the cost of processing and other factors the inner hole of the crankshaft is designed in two different structures, straight-hole and transverse-hole. The structure diagram is shown in Figure 1. The end of the straight hole is located on motor head, however the end of the transverse-hole is on motor bottom. Because of the different position and pressure of the hole end, the influence on the pump oil is also different. Considering rotary compressor is in a hermetic environment with high temperature and pressure, its internal media flow can not be directly observed and tested. The feasibility of schemes only can be indirectly determined by a large number of tests, but the specific difference to the pump oil between two hole structures of the crankshaft can not be explained.
With the rapid development of computational fluid dynamics (CFD) technology, it provides an important way for the study of the internal flow field of the compressor. In 2008, Zhai Zhanli from Xi'an Jiao Tong University simulated double cylinders rotary compressor oil supply system. They analyzed the flow state of lubricating oil in the oil pump crankshaft. In 2010, Santa Catarina Federal University of Marcus V.C. ALVES analyzed lubricating oil processing time to target bearing by simulating spiral pump oil on the reciprocating compressor. In 2012, Professor Liu Chunhui from Shanghai Hitachi Electric Appliance Co., Ltd. established a simulation method for rotary compressor oil pump system. It can analyze the characteristics of the oil pump and the changes in the relations between bearing holes with time. In 2014 Mauricio P. TADA from Embraco Brazil R & D center simulated reciprocating compressor oil pump system, calculating relation of oil eight and volume under different rotary speed. The result is verified by test.

Commercial CFD software is used to simulate compressor oil pump system in this article, and the gas and liquid two phase separation model is also used. The effect of the two kinds of crankshaft structures on the pump oil at different speeds is compared and analyzed to determine the best suitable conditions for them.

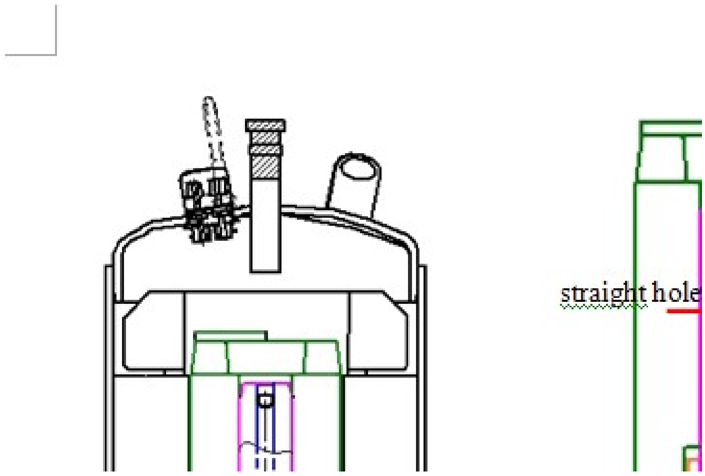


Figure 1: (a)Compressor diagram (b)Crankshaft straight-hole structure (c)Crankshaft transverse-hole structure

2. CFD MODEL

2.1 Fluid Region Model

The simulation of rotary compressor oil pump system is realized by using VOF method to track the flow interface between lubricating oil and refrigerant, so the oil pump system model includes not only lubricating oil flowing through the area, but also some refrigerant domains contacting with the lubricating oil. Taking the inverter double-cylinder compressor as an example, Three-dimension structure model of compressor is established, then fluid regions can be got through the model Boolean operation and the fluid model of the whole pumping system is obtained, including oil pool, crankshaft inner hole, bearing fluid domain, eccentric bearings, bearing on the fluid domain, the fluid domain and part of the refrigerant region, as shown in Figure 2.

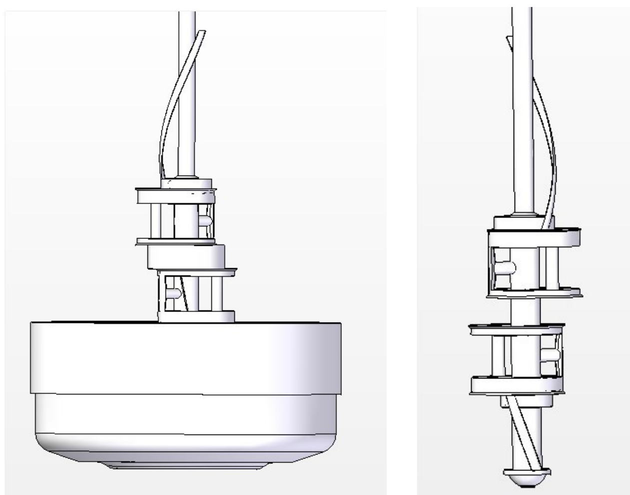


Figure 2: The whole model of the oil-pump system

Compared with the crankshaft straight-hole and transverse-hole structures, the flowing domain for lubricating oil doesn't vary, but the exhaust outlet for refrigerant gas changes. It is shown in the fluid model that the area of the crankshaft inner-hole is slightly different, and the rest areas are the same. The two structural models of straight and transverse holes are shown in Figure 3 (a) and 3 (b), respectively. The color in the picture is no meaning, just to show the parts more clearly.

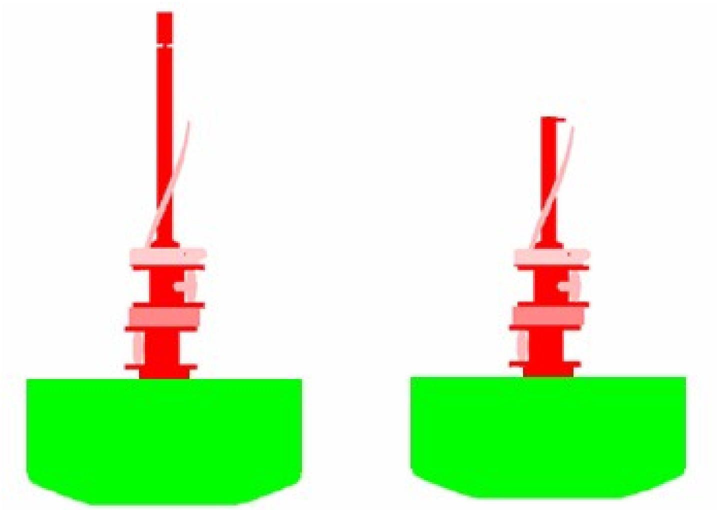


Figure 3: (a) The model of straight-hole structure (b) The model of transverse-hole structure

The simulation of oil-pump system involves dynamic mesh and multi-phase flow VOF model. In order to improve convergence and shorten the computation time, the model is divided into several regions, each of which is divided into grids. The mesh is hexahedral mesh. Each part of the grid model is shown in Figure 4.

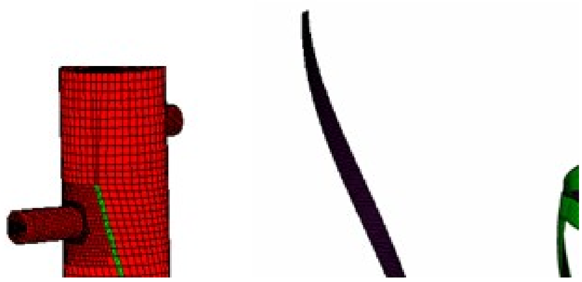


Figure 4: the grid of regions

2.2 Parameter Setting

The fluid medium in the oil-pump model is the coexistence of the R410A refrigerant and HAF68 lubricating oil, the fluid parameters are set up according to the actual working conditions of the compressor. Calculation conditions and parameters are shown in table 1.

Table 1: Calculation conditions and parameters

Pd (MPa)	Td (℃)	ω (rpm)	Refrigerant R410A		Lubricating oil HAF68	
			D (kg/m3)	V (Pa·s)	D (kg/m3)	V (Pa·s)
3.1	95	900/2850/4500/7200	92.532	1.74E-05	900	4.45E-03

A comparative calculation is made at four different speeds. The moving part of the model is the fluid field of the crankshaft inner hole, and the rest parts such as oil pool, middle plate, upper bearing and lower bearing are all stationary. The monitoring surface is set up in the inlet of the dust collecting ring and the radial oil outlet of each bearing of the crankshaft, and the parameters of the lubricating oil and the oil flow rate of the outlet are monitored.

2.3 Boundary Condition

There are three boundaries in the oil-pump model of compressor, Which include a crankshaft straight-hole or a transverse-hole used to discharge the refrigerant in the pump system, the spiral groove outlet in the upper bearing, and the oil pool surface. At these three boundaries, the pressure changes with the variety of compressor working conditions and rotational speeds, and the pressure real-time updates with the crank angle in a period. The biggest difference between the straight-hole and the transverse-hole is the respective real-time pressure curve at the end of hole, which is the key factor to analyze the influence of the two structures on the pump oil.
In order to simulate the oil-pump system accurately, the real-time pressure curve at three boundaries should be obtained. Therefore, the refrigerant flow model of the compressor is established, and the flow field of the compressor exhaust chamber is calculated under different working conditions. The pressure change of the flow field at the boundary is monitored, and the curve of the monitoring point pressure with the crankshaft rotation angle is obtained. The boundary pressure curve that varies with the angle of the crankshaft at different speeds is shown in Figure 5. The end of the transverse-hole is close to the the spiral groove outlet, so the same monitoring point is used.

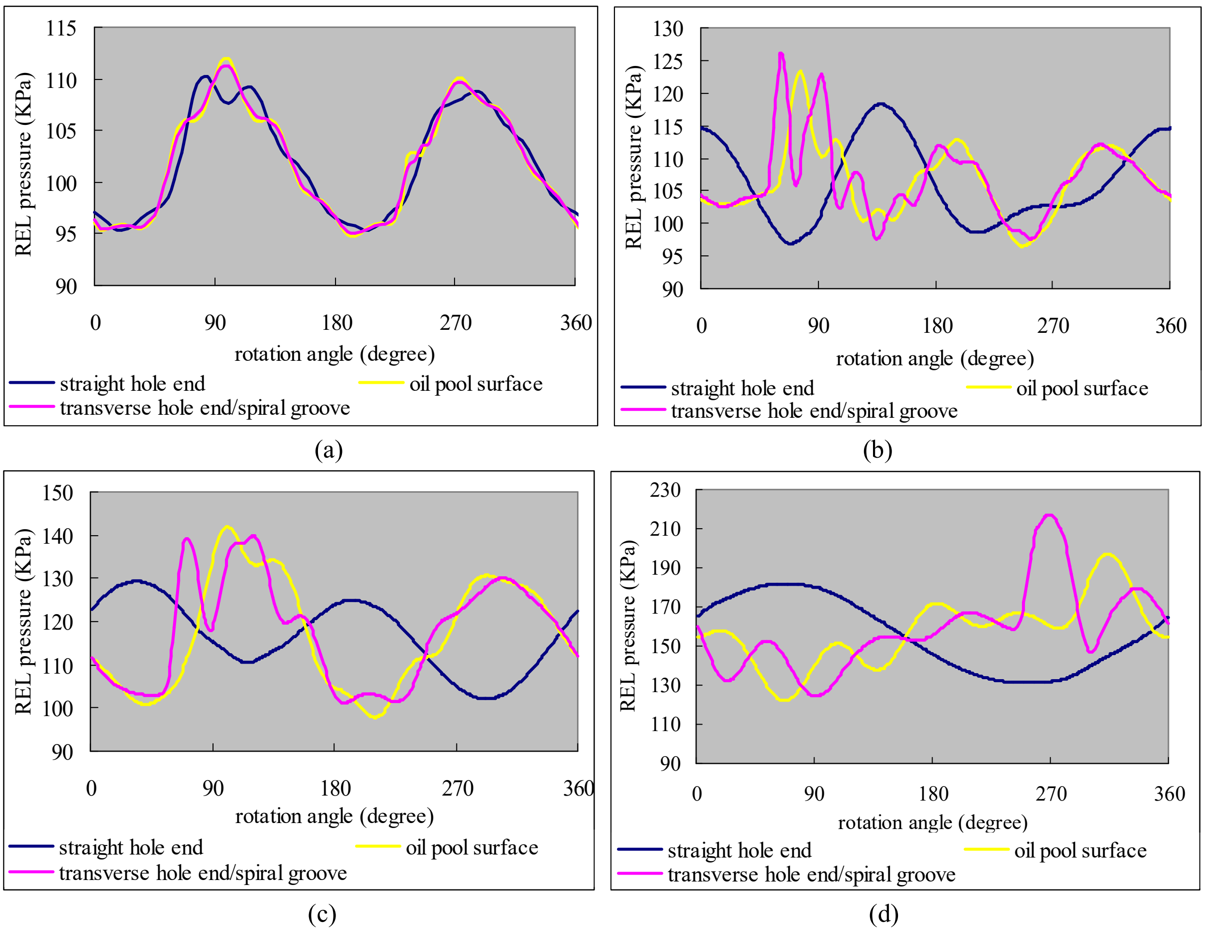


Figure 5: the monitoring pressure at the boundary (a)900rpm (b)2850rpm (c)4500rpm (d)7200rpm

With the increase of speed, the pressure in the exhaust chamber of the compressor increases correspondingly, while the straight-hole end and the transverse-hole end are distributed on the upper and lower two cavities of the motor, and the pressure difference increases with the increase of the speed. The average pressure in one period is calculated.

The average pressure of the straight-hole end and the transverse-hole end which is relative to the oil pool surface pressure is shown in Table 2.

Table 2: The average pressure relative to the oil pool surface

ω（rpm）	Straight-hole end(Pa)	Transverse-hole end(Pa)	Difference between straight-hole and transverse-hole (Pa)
900	-20	10	30
2850	-98	300	398
4500	-430	410	840
7200	-1769	1073	2843

3. PUMP OIL RESULTS

3.1 Pump Oil Characteristics

Simulation of pump oil uses VOF method which is tracking of the moving interface by solving the VOF function. In VOF method the ratio of lubricating oil is expressed through different colors. "1" is all lubricating oil with red, and "0" is all refrigerant with blue. The color in the middle is the ratio of the lubricating oil out of 1.

Figure 6 is an example of lubricating oil distribution diagram in the oil-pump system which runs 2850rpm with straight-hole structure.It can be seen from the diagram that the oil-pump system is divided into two channels, the crankshaft inner hole channel and the crankshaft external channel. In the crankshaft inner hole passage, the lubricating oil is pumped together from the dust ring by centrifugal force and pressure difference with the crankshaft high rotating speed. Then it rises up along the inner wall of the crankshaft and forms U oil surface, and flows through all bearing holes. The higher the rotating speed turns, the greater the centrifugal force forms. The rising speed of the lubricant oil also becomes faster and the rising height is higher. Moreover the dry friction time of all bearings will decrease with the increase of the rotational speed. The crankshaft is equipped with a blade, rotating with the same speed of the crankshaft to promote the movement of the lubricating oil, which will reduce the rise time of the lubricating oil and the dry friction time of the bearing. In the external channel of the crankshaft, the oil out holes of each bearing are connected through the gap, and the oil mass flow of each bearing oil hole is balanced. The oil-pump process characteristics of the two schemes of straight-hole and transverse-hole are basically similar, but the pump oil mass flow will have a significant influence due to the difference of pressure difference.

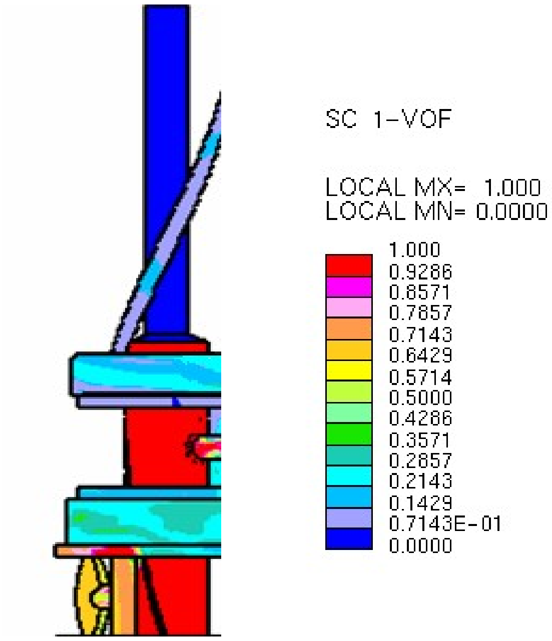
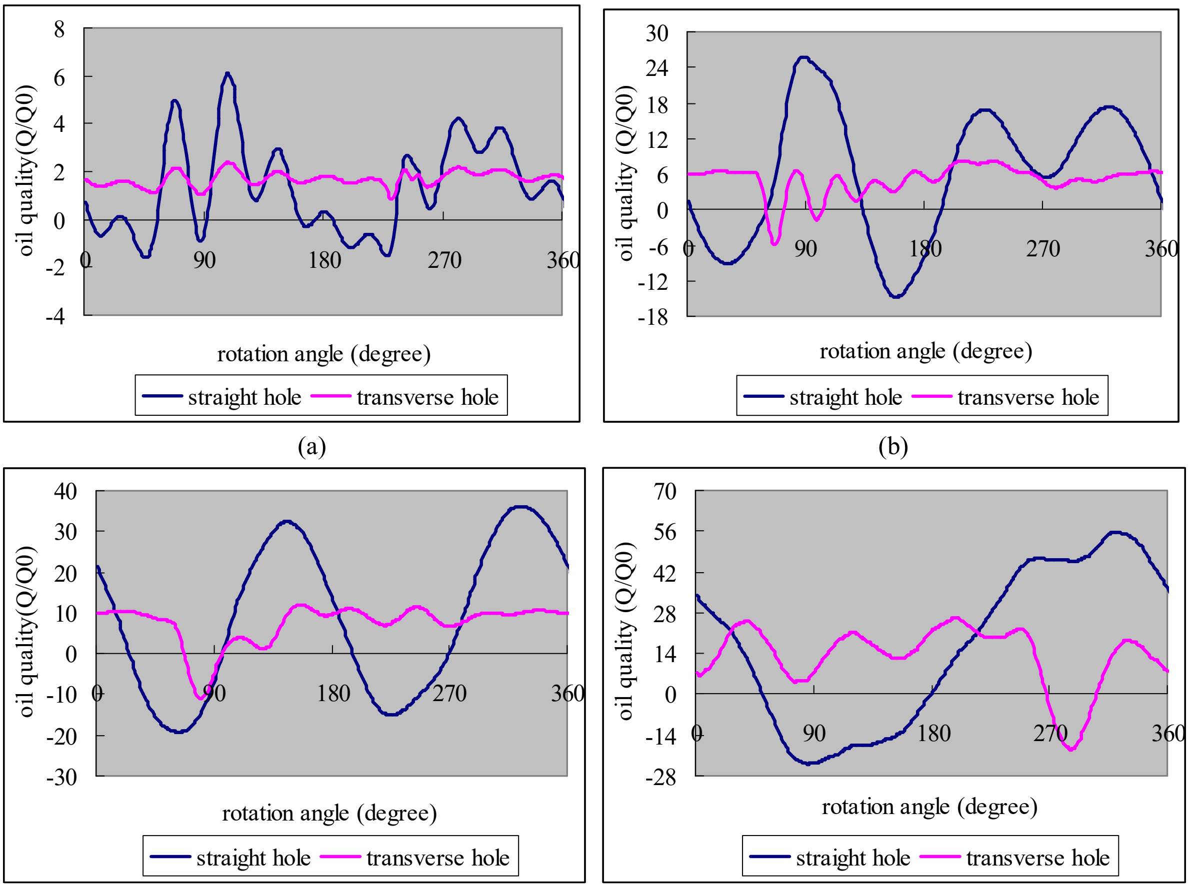


Figure 6: Distribution of lubricating oil in oil-pump system

3.2 Oil Mass Flow

To monitor the lubricating oil flow of the dust ring inlet at the bottom of crankshaft, the oil pumping mass flow curve with the change of time can be obtained. The fluctuation of boundary pressure with time will lead to instability of pump oil mass flow. As mentioned above, the pressure difference curves of the two structures are very different, so the difference of pump oil mass flow is also very obvious. Figure 7 is the change curve of the pump oil mass flow with the crankshaft angle of two kinds of structures, straight-hole and transverse-hole at each speed. The higher the speed turns, the greater the pressure pulsation becomes at the boundaries. And the pulsation of the pump oil mass flow is also the greater. However, the pressure difference pulsation at the straight-hole end is larger than that at the transverse-hole end, the pulsation of the pump oil mass flow with the straight -hole is also larger. Even at some time, the oil mass flow is countercurrent which may affect the bearing force and lubrication.



(a) (b) (c) (d)

Figure 7: Change of pump oil mass flow with rotation angle (a)900rpm (b)2850rpm (c)4500rpm (d)7200rpm

The average pump oil mass flow of two structures at different speeds is compared, and the results are shown in Table 3. With the increase of rotational speed, the pump oil mass flow of the two structures increased significantly. Compared with the straight-hole structure, the transverse-hole pump has more oil mass at the speed of 900 rpm, and with the increase of the speed, the oil mass flow of the 2850rpm, 4500rpm and 7200rpm in transverse-hole pump is above 10% smaller than that of the straight-hole.

The cause of the above results is that the pressure difference between the transverse-hole and the straight-hole is very small when the speed is at the speed of 900rpm, the difference of the average pressure difference is only about 10Pa, which does not have a big influence on the pump oil. Due to the large fluctuation of the straight-hole flow and the large energy loss, the straight-hole pump oil is slightly worse than the transverse-hole. But at the speed of 2850 rpm and above, the pressure difference between the transverse-hole and the straight-hole is very big, and the average pressure difference of the straight-hole is smaller than that of the transverse-hole 390Pa. which has a great influence on the pump oil. Although the straight-hole flow fluctuates and the energy loss is large, the pressure difference plays a major role in the synthesis of the straight-hole. Therefore, the oil mass flow of the straight-hole pump is more than that of the transverse- hole.

Table 3: Comparison results of average pump oil mass flow

ω （rpm）	Straight hole	Transverse hole	Difference between straight hole and transverse hole (%)
900	1.499	1.283	↑ 14.67%
2850	4.726	6.041	↓ 27.66%
4500	7.050	7.916	↓ 12.28%
7200	12.930	15.200	↓ 17.56%

In order to verify the accuracy of the calculation, Continuous life tests of the compressor with the straight-hole structure and the transverse-hole structure were done for 90 days at different speeds. From the aspect of the bearing wear after disintegration, at the low speed transverse-hole is superior and at the high speed straight-hole is superior, which indirectly verifies the CFD calculation results.

4. CONCLUSIONS

After simulating the oil-pump system， the influence of two structures of the straight-hole and the transverse-hole is analyzed, and the following conclusions are obtained:

- The pump oil mass of the compressor crankshaft is determined by two factors, the centrifugal effect caused by the speed and the pressure difference between the outlet of the hole and the oil surface.
- The effect of the pressure difference between the outlet and the oil surface is divided into two parts, the average pressure difference and the intensity of the pressure pulsation. The greater the pressure difference, the higher the pump oil. The more intense the pressure pulsation, the greater the loss, the lower the pump oil.
- Compared with the average pressure difference between straight-hole and transverse-hole, the transverse-hole end is in the lower cavity of the motor, but the straight-hole end is in the upper cavity of the motor, there is a certain pressure loss when the refrigerant flow through the motor, so the average pressure of the upper cavity of the motor is lower than that of the motor lower cavity. Therefore, the average pressure of the transverse-hole end is larger than the oil surface pressure, and the pressure difference is positive, which is unfavorable for pump oil. The average pressure of the straight-hole end is smaller than the oil surface pressure, and the pressure difference is negative, which is favorable for pump oil.
- Compared with the intensity of pressure fluctuation between straight-hole and transverse-hole, the transverse-hole end and the oil surface are both in the lower cavity side of the motor, the pressure pulsation phase difference of them is small, resulting in pressure difference curve fluctuation is small, which is favorable to pump oil. The straight-hole end and the oil surface are in the opposite side of the motor, the pressure pulsation phase difference of them is large and the pressure pulsation is large accordingly, which is unfavorable to pump oil.

NOMENCLATURE

Pd	exhaust pressure	(MPa)
Td	exhaust tempreture	(℃)
ω	rotation speed	(rpm)
D	density	(kg/m3)
V	viscosity	(Pa·s)
Q	oil mass flow	(kg/s)
Q0	base oil mass flow	(kg/s)

Subscript

REL	relative

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